Precision Curved Micro Hemispherical Resonator Shells Fabricated by Poached-Egg Micro-molding

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***Abstract*—This paper presents a new technique for the fabrication of high resolution non-planar precision microshells for hemispherical resonating gyros via a poached-egg micromolding (PEM) method. In PEM, precision ball lenses are used as starting molds. Hemispherical shells are formed on the lenses using five major steps: (1) isotropic coating with sacrificial and shell layers, (2) stencil transfer of coated lenses to substrate, (3) shell top removal by anisotropic etching, (4) sacrificial layer etching and (5) release of the ball lens molds. Using PEM, we fabricated posted sputtered ultra-low-expansion glass hemispherical shells of 1 mm diameter and 1.2 µm thickness. The microshells have better than 120 ppm uniformity in thickness and less than ±0.125 µm deviation from a perfect sphere. The measured microshell resonant frequency at 100 mTorr was 17.32 kHz and the Q was ~ 20,000.**

I. INTRODUCTION

Macroscopic rate integrating gyroscopes are widely used [1-2] for measuring rotation precisely over a wide range of dynamic conditions and extremely large dynamic range with unprecedented accuracy. The most successful implementation is the hemispherical resonant gyroscope (HRG). This device relies on the quasi stationary behavior of a single vibration mode oscillating on a precision radially symmetric shell. HRG devices are constructed in either wine-glass or domed configurations. Despite its noteworthy advantages, rate integrating gyroscope technology has not been demonstrated on the microscale due to the difficulties associated with the shell construction. Present MEMS microfabrication technologies utilize planar processes where the dimensional precision is determined by the resolution of lithographic process, on the scale of 0.5 µm and thickness control for most films is about 5%. Therefore fundamentally planar MEMS technology is not feasible for the fabrication of ultra-high precision HRGs, and in general, it cannot be used for the batch fabrication of continuously curved three-dimensional shell microstructures.

In this paper, we present a micromolding batch fabrication technique which enables the fabrication of hemispherical structures of ultra-high precision. The process is based on the use of spherical molds, deposition and etching as discussed below. The process can be applied for the microfabrication of curved shells in a diverse range of applications.

II. HRG SHELL SCALING

The HRG utilizes the rotation sensitivity of the lowest bending mode of a hemispherical shell. When the HRG is vibrating in that mode it will respond in one cycle of the shell vibration by deforming from spherical to ellipsoidal during the first quarter of the cycle, returning to spherical during the second quarter, deforming into an ellipsoidal shape during the third quarter but with the semi-major and semi-minor axes of the ellipse interchanged, and returning to its original spherical shape during the fourth quarter of the cycle as shown in Fig. 1. The resonating wobbling of the HRG shape has its own inertial frame; hence one can detect rotation by monitoring the relative angle of the vibration principal axes respect to a rotating frame.

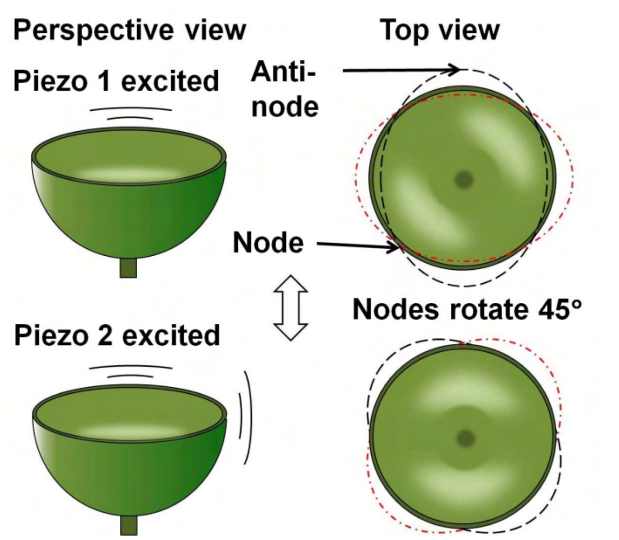

Figure 1. Vibrating modes of HRG shell used for gyroscopic sensing applications.

In order to achieve high accuracy in the gyroscopic measurements, a very high resonator Q is needed, typically in the 10^5-10^6 range which imposes challenging resonator

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requirements for the resonator materials and the dimensional control. There are several important factors that need to be considered when scaling the HRG dimensions. The first is dimensional precision. Conventional high-precision HRGs are typically 2-6 cm in diameter and 1-2 mm in thickness. Since for this device $r \gg h$, the dominant dimension impacting the device performance is the shell thickness uniformity. Thickness control for navigation-grade HRG devices requires trimming the shape to within 0.1 µm, a dimensional control of 0.005%. Such level of accuracy in itself presents a tremendous challenge in the miniaturization of the HRG device. Shrinking down the thickness of the shell to 1 µm requires a dimensional control of about 0.1 nm. This immediately translates in the need of atomic monolayer thickness control. The second consideration is the impact of scaling on the HRG resonant frequency, and its ultimate effect on the resonator Q and free oscillation decay time. The HRG resonant frequency depends on its oscillation mode number n (typically 2) and is given by

$$\omega = \frac{n(n^2-1)h}{r^2}\sqrt{\frac{E}{3(1+\mu)\rho}} \cdot \sqrt{\frac{I(n)}{J(n)}} = a(n)\frac{h}{r^2}\sqrt{\frac{E}{3(1+\mu)\rho}}$$

where r is the shell radius, h is the shell thickness, ρ is the shell density, μ is Poisson's ratio, and the remainder is a unit-less scaling factor of the mode number ($a(2) \cong 2.62$). The Q of the structure is limited by thermoelastic, support and other loss mechanisms. The thermoelastic Q limit for hemispherical shell structures has been calculated in [3] and the damping behavior of resonators in connection to material properties is discussed in [4-5]. While the derivation of the ultimate Q is beyond the scope of this paper, in general, materials with a high thermal conductivity and low thermal coefficient of expansion produce the lowest thermoelastic losses. Low loss resonators can be made of materials close to quartz such as ultra low expansion glass (ULE) [6]. ULE, Corning Code 7972 is a titanium silicate glass with unique characteristics that has made it the material of choice in low-expansion applications ranging from machine tool reference blocks to solid and lightweight mirror blanks. In this paper we fabricated ULE shells on curved micromolds using the poached egg molding method (PEM) discussed below.

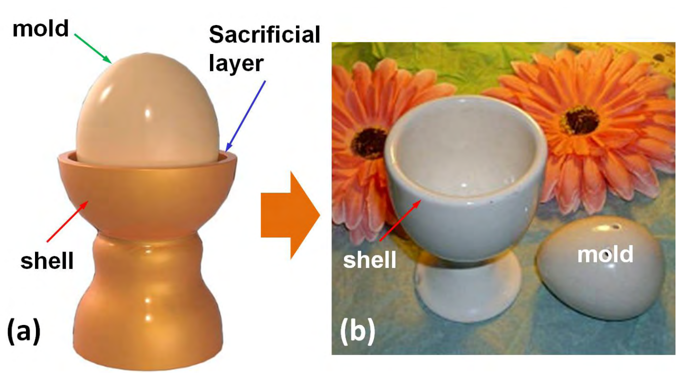

Figure 2. Illustration of the poached-egg molding concept. A spherical mold is coated with a shell and release layer. After immobilization, the shell top is removed and the mold is released.

III. The Poached-Egg Micro-Molding Method

Figure 2 shows an illustration describing the concept of poached-egg molding as a fabrication method for shells. First a spherical mold coated with both sacrificial and structural shell layers is immobilized to a substrate. Next the shell and sacrificial films on top of the ball are removed via anisotropic etching thus forming a hemispherical coating on the mold as the mold itself serves as a mask layer protecting the bottom of the shell. After removal of the sacrificial spacer layer, the mold can be removed leaving the supported hemispherical shell attached to the substrate. The final structure thus resembles a thin-walled goblet as shown in Fig. 2(b).

The precision of the shells formed by the PEM method is determined by that of the mold used. Curved glass components are commonly used in optical systems. Such components are fabricated with sub-micrometer precision using diamond turning techniques. In our fabrication method we use sapphire ball lenses with absolute diameter precision of ±250 nm as starting molds as shown in Fig. 3(a). Once the

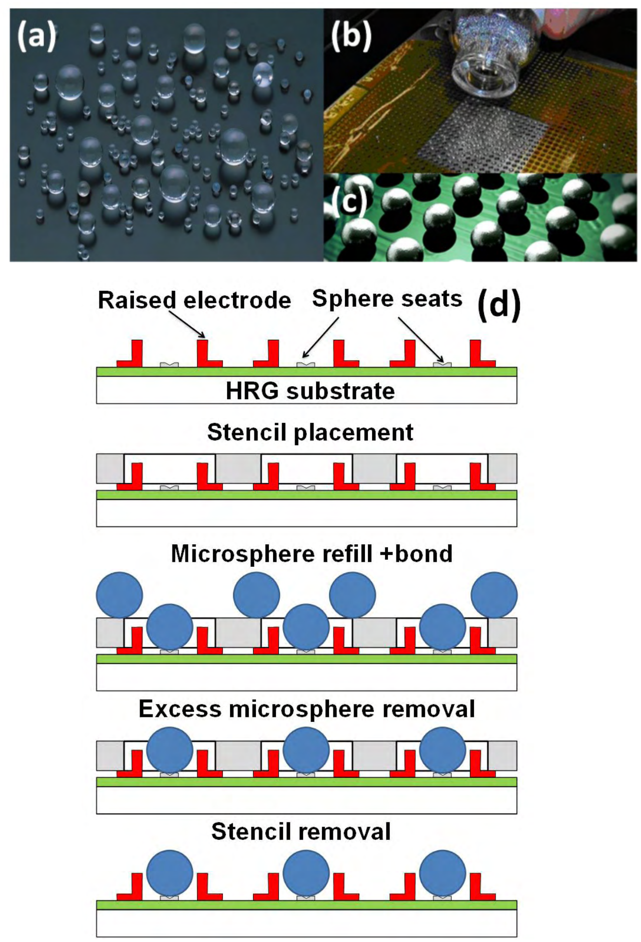

Figure 3. Stencil based process for transfer of precision microspheres to the HRG substrate.

molds are selected, they are coated with a very uniform layer of sputtered silicon sacrificial layer and sputtered ULE glass. Next the coated lenses are transferred and bonded to posts on a flat substrate using a stencil in a very similar way as the transfer process of solder balls for BGA substrates as shown in Figure 3 (b-d). After sieved by the stencil, the coated ball lenses are bonded at their seats. The bonding can be formed using a thermally activated material such as glass frit. Finally the molded shells are formed by removing the shell top using anisotropic etching followed by sacrificially etching away the silicon spacing layer and final mold release.

IV. DETAILED FABRICATION PROCESS

Figure 4 shows a more detailed fabrication procedure of the HRG shell. 1 mm-diameter, precision lenses are first coated with a layer of 4 µm sacrificial sputtered silicon and a layer of 1.2 µm thick sputtered ULE glass (SULEG) before the coated molds are placed and immobilized on the HRG substrate. During the deposition process of the sacrificial silicon and ULE sputtering, the lens is under constant motion of rolling, which ensures the conformal coating of the materials on the entire surface exposed, even the bottom-half of the spheres.

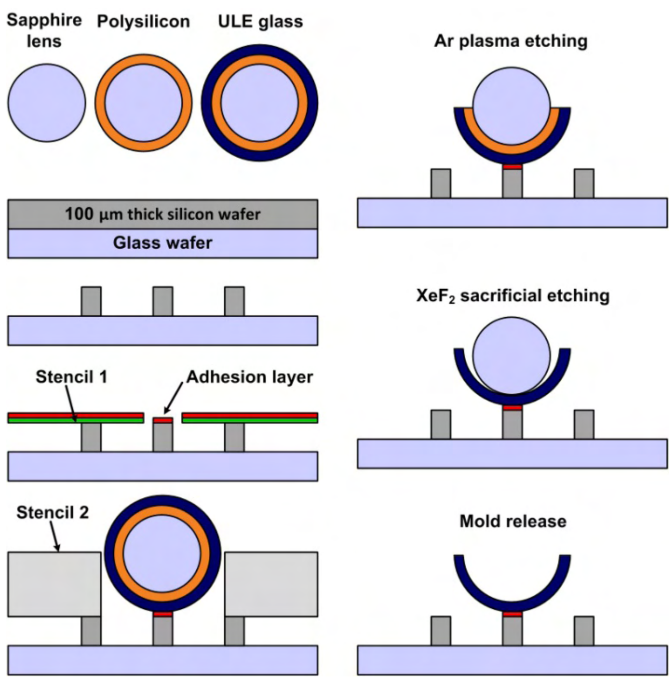

Figure 4. Detailed fabrication procedure of precision curved micro spherical shells.

The fabrication of the holding substrate is as follows. First, a double side polished silicon wafer 100 µm-thick is anodically bonded to a 7740 glass wafer. Pre-bonding cleaning including piranha clean and BOE dip has been carried out for the silicon wafer while for the glass wafer only Piranha clean is carried out. The mold bonding posts are next formed by lithographic feature patterning and DRIE. Next the substrate is coated with a layer of 0.5 µm sputtered silicon oxide which serves as a protection layer for the silicon bonding post from the shell sacrificial layer etching. After application of a very thin layer of bonding agent on the post through a stencil, the coated lens is positioned on the post with the help of a second stencil. Next, the stencil is removed, and the coated mold is bonded. The top half of the shell including both the top half of the ULE coating layer as well as the top half of the sacrificial silicon coating layer are next ion-milled in Ar at a pressure of 10 mT. During this step, the top of the sphere mold serves as a self-aligned mask for the hemi-spherical shell remaining below. Next, the sacrificial silicon layer is removed with XeF_2 etching for about 6 hours. After the etching is completed, the substrate is flipped which automatically drop offs the molds by gravity pull, leaving the released hemisphere shells attached to the substrate.

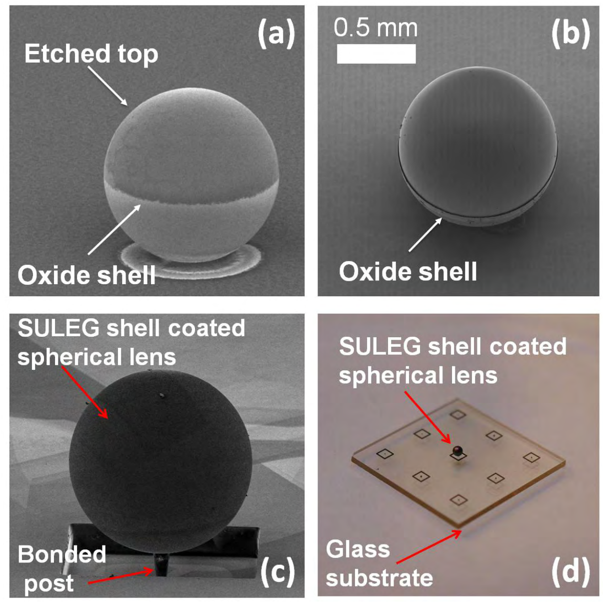

Figure 5. SEM and optical pictures of fabricated ULE shell devices using the PEM technique.

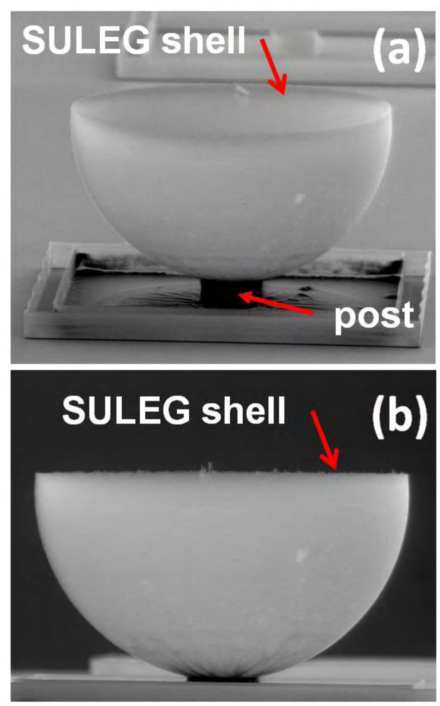

Figure 6. SEM pictures of released SULEG shell.

Figures 5 (a) and (b) shows SEM pictures of a lens with top material etched away. From the SEM pictures, we can clearly see the etching front resulting from the effect of self-aligned. Figures 5 (c) and (d) are SEM and optical pictures showing a coated lens bonded to a supporting substrate. Figures 6 (a) and (b) shows SEM pictures of the final released shells. The dimensional deviation of the released shell from a sphere mold is about ± 0.125 – 0.3 µm.

V. TESTING AND EXPERIMENTAL RESULTS

The resonance frequency of the posted shell was characterized using the experimental vacuum opto-mechanical setup shown in Figure 7.

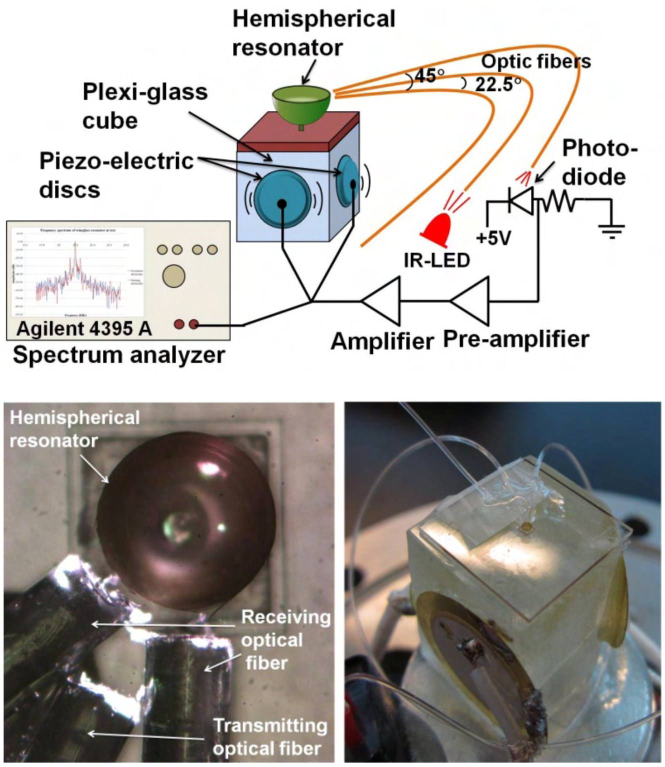

Figure 7. Experimental setup. The whole setup was placed in a vacuum chamber pumped down to 100 mT during the test.

The substrate with the device was mounted on a plexi-glass cube with ceramic piezoelectric discs mounted on its sidewall for device actuation. Optic fibers (500 µm diameter) were manually assembled along the rim of the hemisphere. The optical fibers were arranged in a way that they separate from each other with an angle about 22.5°. The center fiber was then used to illuminate a section of the hemispherical rim sufficient to couple light back into the two adjacent sensing fibers. An infrared LED was used for illumination and a photo-diode was used for sensing. The AC current produced in the photo-diode due to the shell vibration was passed through a resistor whose voltage was then amplified and analyzed in an Agilent 4395A spectrum analyzer. The whole measurement setup was then placed in a custom built vacuum chamber with electrical feedthroughs for testing. Measurements were carried out at a chamber pressure of 100 mT.

The piezoelectric discs were driven in a positive feedback mode till a stable oscillating condition (resonance) was attained. The technique is based on the assumption that the white noise from the amplifiers would be sufficient to produce enough vibrations in the piezoelectric discs to actuate the shell. The shell filters out all but the resonant frequencies and the driving signal becomes stronger with every pass through this loop.

Figure 8 shows the frequency spectrum of the shell with the resonant peak prominent. The measured resonant frequency was 17,320 Hz with Q factor of around 20,000. The absence of any other peaks in the vicinity of the resonant frequency is indicative of the high degree of sphericity of the shell. A large deviation in sphericity would give rise to multiple/split peaks depending on the extent of deviation. The single peak also implies that the spurious modes of vibration are either suppressed or widely separated in frequency.

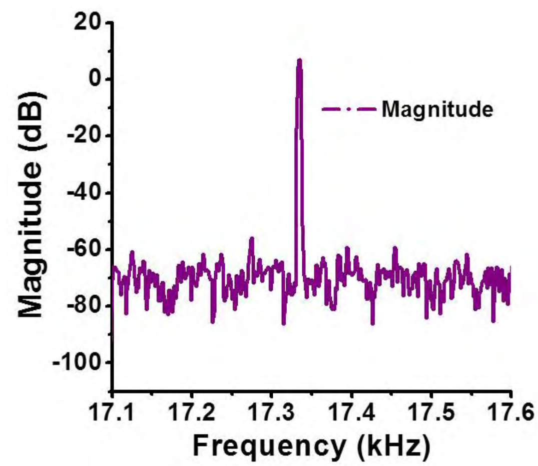

Figure 8. Measured resonator shell spectrum. The Q factor is approximately 20,000.

VI. SUMMARY

We present a new poached-egg micromolding technique for the fabrication of precision curved micro structures. In particular, we demonstrate the feasibility of this technique by fabricating hemispherical resonating gyroscope shells. The fabricated microshells have uniformity better than 120 ppm in thickness and less than ±0.125 µm deviation from a perfect sphere. Such hemispherical shells have important applications in rate-integrating inertial navigation systems.

REFERENCES

[1] D. M. Rozelle, "The hemispherical resonator gyro: from wineglass to the planets", Proc. 19th AAS/AIAA Space Flight Mechanics Meeting, pp. 1157-1178, 2009.

[2] A. Meyer, D. M. Rozelle, "Milli-HRG inertial navigation system", Proc. of IEEE/ION PLANS 2012, pp. 24-29, 2012.

[3] S. Y. Choi, Y. H. Na and J. H. Kim "Thermoelastic damping of inextensional hemispherical shell", Proc. World Academy of Science, Engineering and Technology, 56, pp. 198-203, 2009.

[4] A. Duwel et al, "Quality factors of MEMS gyros and the role of thermoelastic dampling" Proc. IEEE MEMS conference, pp. 214-219, 2002.

[5] Z. Hao and F. Ayazi, "Thermoelastic damping in flexural-mode ring gyroscopes", Proc. IMECE 2005, ASME, IMECE 2005-79965, pp. 1-9, 2005.

[6] D. Gerlich, M. Wolf, I. Yaacov and B. Nissenson, "Thermoelastic properties of ULE titanium silicate glass", Journal of Non-Crystalline Solids, 21, pp. 243-249, 1976.